Technical University
of Denmark

Using acoustic fish telemetry to evaluate impact of river diverging: implications for anadromous brown trout (*Salmo trutta*) utilizing a marine protected area

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Forord

Tak til Foreningen for ophjælpning af fiskeriet i Roskilde Fjord samt, Roskilde og Omegns Lystfiskerklub (ROLK) for sammenarbejdet og indsamling af data, herunder Uffe Clementsen og Torben Trampe. I særdeleshed stor tak til Jonn Poulsen og Kim Lund Jørgensen for en stor indsats i indsamling af data og feltarbejde på Roskilde Fjord. Jeg takker ligeledes Hugo M. Flávio, Eleanor Williams og Jon C. Svendsen for behjælpelighed med databehandling og konstruktiv feedback. Dette studie blev udført i overensstemmelse med dansk regulering inden for velfærd og behandling af forsøgsdyr. Dette speciale indeholder et dansk resume, samt min afhandling som er præsenteret som et udkast til en artikel. Da afhandlingen er præsenteret i et artikelformat, er det det danske resume inddraget for at give et indtryk af hvad jeg har udført af arbejdsopgaver under mit speciale.

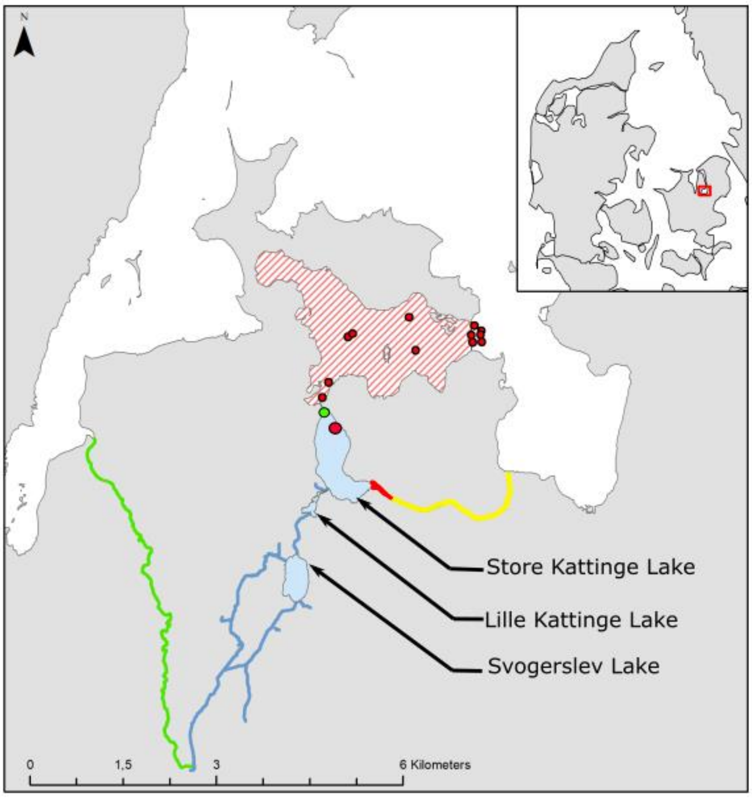
Projekt titel: Anvendelse af akustisk telemetri til at evaluere effekten af omlægning af åløb: implikationer for anadrome ørred som anvender marint beskyttet område

Projekt title: Using acoustic fish telemetry to evaluate impact of river diverging: implications for anadromous brown trout (*Salmo trutta*) utilizing a marine protected area

Dansk speciale resume

Dette danske resume har til formål at opsummere formål med projektet, konklusionen på projektet samt præsentere, hvilke arbejdsopgaver jeg har udført under specialet. Alle resultater, pointer og konklusioner i dette danske resume er præsenteret og gennemgået dybdegående i afhandlingen, som starter på side 18.

Introduktion og formål



Figur 1 viser et kort over den sydligste del af Roskilde Fjord, der giver et overblik over det marint beskyttede område (rød skravering), lytteposter (røde prikker), stemmeværket og fiskepassagen (grøn prik), Langvad Å (blå streg), de tre søer (lyseblå skravering), Gedebæk renden (gul streg), omlægningsplanen for Langvad Å (rød streg) og den alternative løsning – omlægning af Langvad Å over i Lejre Å (grøn streg). Havørreds gydning foregår hovedsageligt opstrøms området ved Lejre Å.

Som medlem af Den Europæiske Union (EU) er Danmark gennem Vandrammedirektivet forpligtet til at beskytte søer, vandløb, kystvande og grundvand. Herunder har Danmark forpligtet sig til at sikre fri fiskepassage i vandløb samt opnå god tilstand i de fleste danske vandløb (European Commission, 2003). Det vil sige, at vandløb skal leve op til krav jf. Vandrammedirektivet. For åer, som er under 2 meter brede, er et krav f.eks. at leve op til god økologisk tilstand jf. DFFVø ørred indeks. For at et givent vandløb kan klassificeres som havende god økologisk tilstand, skal det jf. DFFVø indekset f.eks. indeholde 80 ørred yngel pr 100 km^2. For at sikre fri passage og derved leve op til

Vandrammedirektivets krav om fri passage for fisk, er det blevet vedtaget, at Langvad Å i Roskilde Fjord bliver omlagt. Åen vil fra udgangen af 2019 blive lagt over i Gedebæk renden (Figur 1). Herefter vil udløbet fra Langvad Å ikke længere løbe ud i Kattinge Vig, men i stedet løbe ud i den sydlige del af Roskilde Fjord (Figur 1). Kattinge Vig har siden 2005 været et marint beskyttet område (engelsk MPA). Dette betyder at trolling, dørgefiskeri og brug af nedgarn er forbudt inde i dette område. Årsagen til at forvaltere indførte et marint beskyttet område var at havørred bestanden i Langvad Å ikke kunne opretholde sig selv. Ved at ulovliggøre visse typer fiskeri, forsøgte forvaltere at mindske fiskeri trykket og herigennem øge den marine overlevelse for havørred. På sigt skulle dette føre til at havørred bestanden i Langvad Å blev selvreproducerende. I dette studie har jeg sporet 50 havørreds vandring i Roskilde Fjord ved brug af akustiske mærker. Jeg har, ud fra vandringsmønsteret estimeret, i hvilket omfang det marint beskyttede område beskytter havørrederne som det første studie af sin slags i Danmark. Ligeledes har vi analyseret og anslået effekten af at flytte Langvad Å samt evalueret den potentielle effekt af omlægningen af Langvad Å. Slutteligt har jeg på baggrund af resultater fra dette studie og eksisterende litteratur udarbejdet alternative løsningmuligheder.

Resume og konklusion

Et fundamentalt element, for at marint beskyttede områder kan beskytte fisk, er, at fiskene opholder sig inde i det beskyttede område. Flere kritikere mener derfor, at anvendelsen af marint beskyttede områder til at beskytte mobile fisk, så som havørred, ikke er muligt eller hensigtsmæssigt, da netop mobile fisk er tilbøjelige til at bevæge sig uden for det beskyttede område. Herved er fiskene ikke beskyttet. Resultater fra dette studie viser, at alle havørreder har brugt minimum 50% af tiden inde i det lille marint beskyttede område (3,82km^{-2}) placeret i Kattinge Vig (Figur 1). Undersøgelsen af havørredernes marine overlevelse indikerede en marin overlevelse på 23%. I alt forsvandt 14 havørred inde i det beskyttede område, og 22 havørred forsvandt uden for det beskyttede område.

Undersøgelsen indikerer, at 11 ud af 14 havørreder, som forsvandt inde i det beskyttede område, sandsynligvis blev fanget af fiskere. Da der ikke er fortaget en undersøgelse af havørredens marine overlevelse forud for implementeringen af det marint beskyttede område, har det ikke været muligt at konkludere, hvorvidt det marint beskyttede område genererer højere marin overlevelse for beskyttede havørreder. Dog har andre studier påvist, at garnfiskeri, som er forbudt i det marint beskyttede område, står for omkring 10% af den samlede mængde af hjemtagende havørred på årsbasis. På dette grundlag kombineret med resultater, som viser at havørrederne opholder sig inde i det marint beskyttede område en stor del af tiden (>50%), estimerer jeg, at det beskyttede område sandsynligvis forhøjer den marine overlevelse.

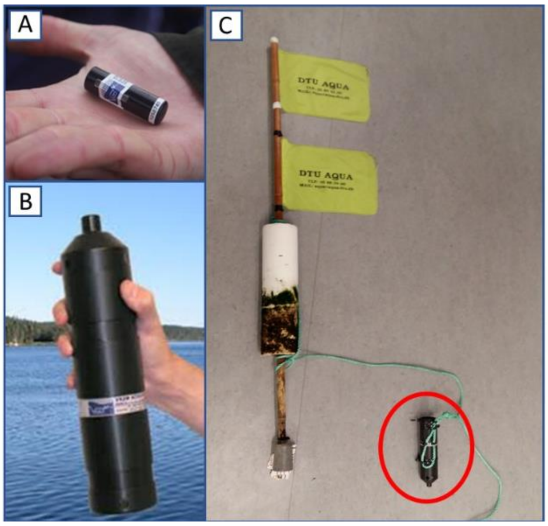
Tidligere studier har vist, at smolt dødeligheden i å-systemer, som løber gennem søer, er mellem 74% til >90% (Jepsen, Aarestrup, Økland, & Rasmussen, 1998; Schwinn, Aarestrup, Baktoft, & Koed, 2017). Resultater fra Schwinn et al. (2017) indikere også at forhøjet smolt dødelighed kan kompromittere en havørred bestand evne til at være selvreproducerende. På nuværende tidspunkt løber Langvad Å igennem søerne Svogerslev sø, Lille Kattinge sø og Store Kattinge sø. Resultater fra Henriksen (1998) viste en smolt dødelighed på 88% for smolt som vandrede gennem de tre søer. Henriksen (1998) og Henriksen (2016), argumentere at årsagen til at havørred populationen i Langvad Å ikke er selvreproducerende skyldes den høje smolt dødelighed. Den nuværende plan om at omlægge Langvad Å tager afsæt i at sikre fri fiskepassage til og fra Langvad Å. Derfor er det ikke planlagt at omgå de tre søer i Langvad Å. Da Langvad Å efter omlægningen til Gedebæk renden stadigvæk vil passere de tre søer (Figur 1), estimere jeg at smolt dødeligheden i Langvad Å vil forblive omkring 88%. Efter omlægningen vil udløbet af Langvad Å ikke længere være beskyttet af det marint beskyttede område. Dette medfører at havørred som opholder sig omkring udløbet, ikke vil være beskyttet for fiskeri. Da smolt dødeligheden forventes at forblive ca. 88% kombineret med at havørred som opholder sig området omkring udløbet mister beskyttelsen fra det marint beskyttede område, forventes det ikke at den nuværende omlægning af Langvad Å vil opnå god økologisk tilstand jf. DFFVø ørredindeks. Dog vil den nuværende løsning sikre fri fiske passage, og derved leve op til kravene under Vandrammedirektivet. På baggrund af resultater fra dette studie har jeg fremsat en løsningsmulighed, som både vil sikre fri passage og potentielt set muliggøre en selvreproducerende bestand af havørred i Langvad Å – og herigennem opnå god økologisk tilstand jf. DFFVø ørredindeks. Løsningen bygger på, at lede vandet fra Langvad Å over i Lejre Å. Herved omgås de tre søer, samt der sikres fri passage. Ved at gøre dette, forventes smolt dødeligheden at falde (Jepsen et al. 1998; Boel and Koed, 2013; Schwinn et al. 2017; Schwinn et al. 2018). Det forventes at en reducering i smolt dødelighed, vil forsage øget returnering af gydemodne havørred de kommende år (Crozier & Kennedy, 1993; Elliott, 1993). Herved mener jeg, at densiteten af ørred yngel i Langvad Å har potentiale til at stige. Herved kan det blive muligt at øge havørred yngeldensiteten fra de nuværende 17 yngel pr 100 km^2 til 80 ørred yngel pr 100 km^2 (I overensstemmelse med DFFVø ørredindeks). Resultater fra dette studie viste, at 62% af alle havørreder (inklusiv havørreder der blev fanget m.m.) blev i den sydlige del af Roskilde Fjord (syd for Frederikssund; figur 3). Ligeledes indikerer data, at det rekreative fiskeri står for mindst 23% af den marine dødelighed. På baggrund af dette vurderer jeg, at en udvidelse af det marint beskyttede område samt skærpelse af regler for lystfiskeri i samspil med de nuværende planer om omlægningen af Langvad Å til dels vil sikre en bæredygtig bestand af havørreder i Langvad Å.

Lokalt sammenarbejde

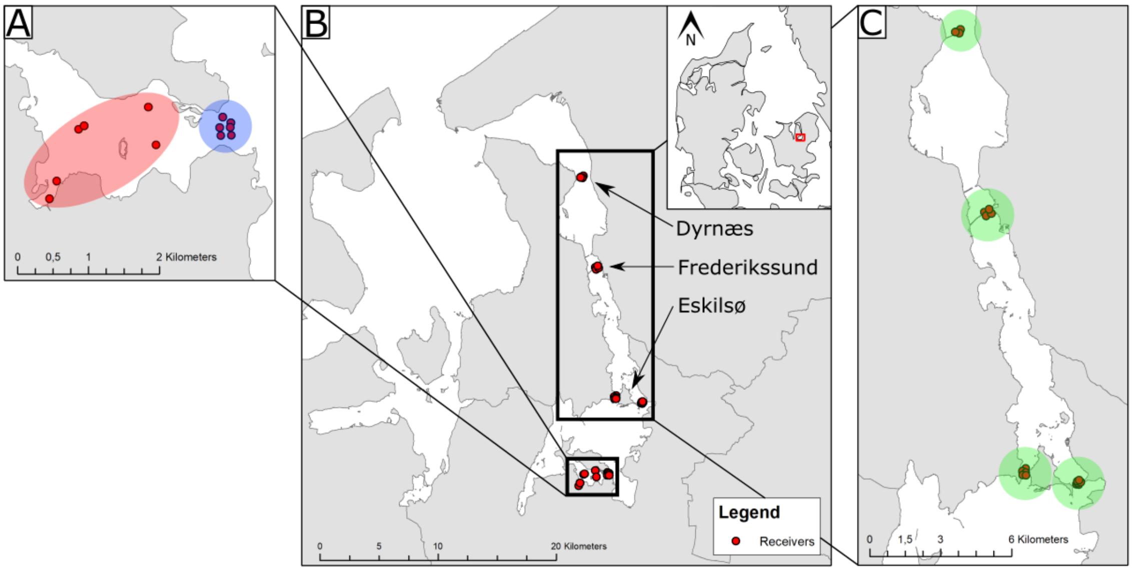
Projektet blev udført i tæt sammenarbejde med medlemmer fra interesseorganisationer i og omkring Roskilde Fjord. Herunder Foreningen til ophjælpning af fiskeriet i Roskilde Fjord og Roskilde og Omegns Lystfiskerklub (ROLK). Jeg stod for koordinering, logistik og kommunikation vedr. feltarbejde mellem medlemmer fra ROLK og DTU Aqua.

Akustiske mærker og lytteposter

For at kunne monitere havørredernes vandring i Roskilde Fjord blev der i dette studie anvendt akustiske mærker og lytteposter (figur 2). De akustiske mærker blev indopereret i voksne havørreder fanget i Langvad Å. I alt blev 36 lytteposter opstillet seks forskellige steder i Roskilde fjord (figur 3), samt en lyttepost placeret i Store Kattinge Sø (Figur 2). Når en mærket havørred svømmer forbi en lyttepost, registrerer lytteposten signalet. De anvendte akustiske mærker var af typen V13T (VEMCO, 2019a), som også registrerer havørredens temperatur. Lytteposterne var af typen VR2W (VEMCO, 2019b). Med denne type udstyr har lytteposterne en detektionsradius på op til ca. 500 meter.



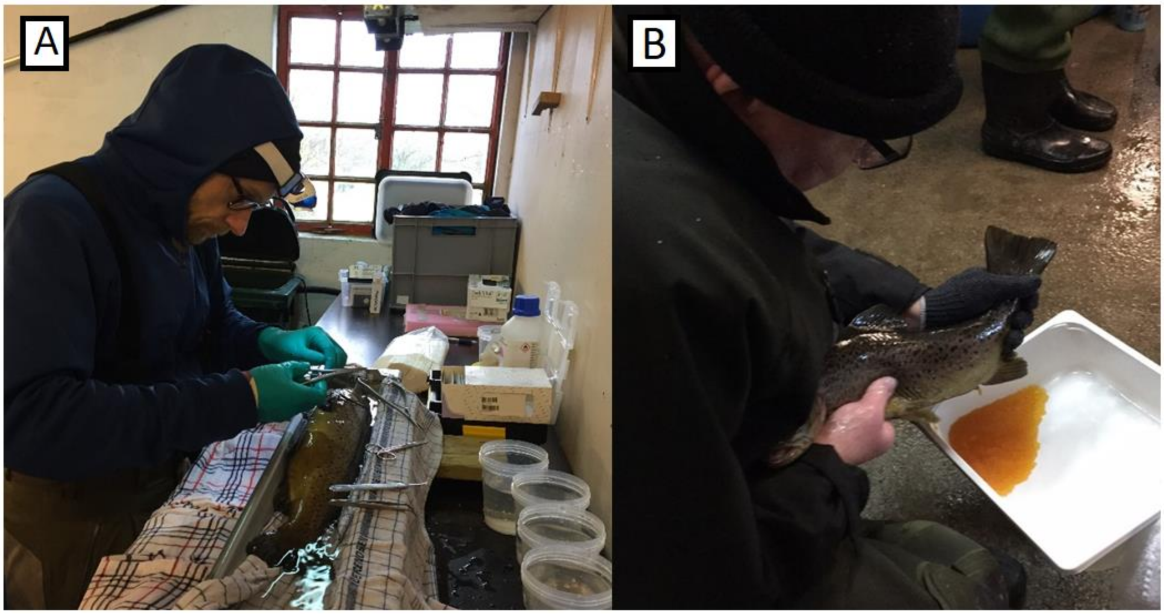
Figur 2 viser akustisk transmitter (foto A), som bliver indopereret i havørrederne. Transmitteren udsender et signal, som registreres af lytteposterne (foto B). Lytteposterne er monteret på flagbøjer (foto C). Lytteposten (foto C, rød cirkel) er monteret ca. 1 meter under flagbøjen.



Figur 3 viser et kort over Roskilde Fjord og illustrerer lytteposternes placering. Lytteposterne er placeret i Kattinge Vig (det marint beskyttede område) (foto A) og ved hhv. Dyrnæs, Frederikssund og Eskilsø (foto B og C).

Mærkning af ørred

Forud for evalueringen af det marint beskyttede område blev 50 havørreder mærket med én akustisk sender pr. havørred. I sammenarbejder med Foreningen for ophjælpning af fiskeriet i Roskilde Fjord og ROLK blev ørrederne fanget i fisketrappen i Langvad Å. Ørrederne blev mærket hhv. d. 14. december 2017 og d. 12. januar 2018. Det var imidlertid planlagt, at alle fisk skulle mærkes og udsættes d. 14. december 2017, men grundet ringe opgang af gydemodne havørred i Langvad Å var dette ikke muligt. Dette medførte imidlertid at havørrederne blev mærket og sat ud af to omgange. Forud for mærkningen blev alle havørreder strøget for sperm og æg (figur 4). Æg og sperm bruges til at producere ørredyngel, som udsættes som yngel i Langvad Å og mundingsudsætning af smolt i Langvad Å systemet. Havørrederne blev mærket af Jon Christian Svendsen (Figur 4A).



Figur 4 viser Jon C. Svendsen, som indopererer de akustiske transmittere i en havørred (foto A). På foto B ses Jonn Poulsen stryge en havørred for æg. Disse æg bruges til at opdrætte ørredyngel og smolt til udsætning i Langvad Å.

Feltarbejde i Roskilde Fjord

Feltarbejdet i Roskilde Fjord indeholdt flere opgaver. Herunder opstilling af lytteposter, vedligeholdelse af udstyr, indsamling af data, koordinering og sikring af udstyr i vintermånederne.

Feltarbejdet blev udført ca. 3-7 gange månedligt og var periodevist besværliggjort af dårlige vejrforhold og isdække på fjorden.

Indsamling af data, vedligeholdelse og kontrol af udstyr

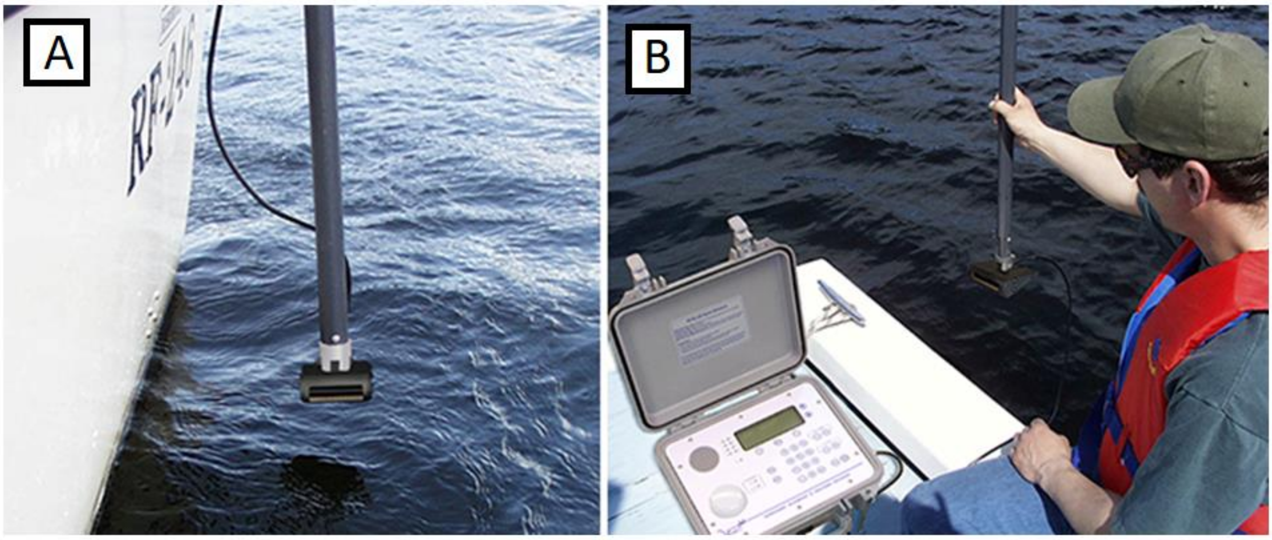
Lytteposterne anvendt i dette studie oplagrer information (data) fra mærkede havørreder, som er blevet registreret. Med typen af lytteposter som er anvendt i dette studie (VR2W), er det nødvendigt at indsamle data manuelt fra en båd. Ved hyppig indsamling af data fra lytteposterne undgik vi at tabet af lytteposter kompromitterede datasættet. Data blev indsamlet i tæt samarbejde med Jonn Poulsen og Kim Jørgensen. Igennem projektets løbetid mistede vi seks hydrofoner. Med hjælp fra en lokal dykkerforening blev den ene lyttepost fundet igen, og en anden blev fundet på land af en lystfisker. Dette resulterede i, at kun fire lytteposter gik tabt. Grundet hyppig indsamling af data fra lytteposterne, gik vi gennemsnitligt ”kun” glip af data for 9 dage pr. tabt lyttepost. Da der inden opsætning af lytteposter blev taget højde for eventuelt tab af udstyr, blev der på alle lyttepoststationer sat ekstra lytteposter i vandet. Herved kompromitterede tabet af lytteposter ikke dækningsgraden af lytteposterne. Det vil sige, at havørreder som passerede forbi eller opholdt sig nær lyttepoststationerne, uafhængigt af tab af enkelte lytteposter, blev registeret af andre lytteposter. Den ene af de to lytteposter, som vi fik tilbage, havde spor af at være blevet sejlet ned af en motorbåd. Flere faktorer i Roskilde Fjord gjorde det nødvendigt at kontrollere og vedligeholde udstyret ofte, blandt andet på grund af kollision mellem lytteposter og både, kraftig strøm som tyngede lytteposterne ned, fiskeredskaber som sat fast i udstyret (gællegarn, ruser og fiskeliner), kraftig vækst af rur (*Balanidae)* og isdække. På trods af ovenstående problemstillinger, blev det ved brug af test-transmittere bekræftet, at samtlige lytteposter inkluderet i projektet var fuldt ud funktionsdygtig igennem hele projektet. Data fra lytteposterne blev indsamlet med VUE-software (VEMCO, 2019c).

Koordinering og sikring af udstyr

Undervejs i projektet opstod flere komplikationer som krævede kreative løsninger. Heriblandt var de to største problemstillinger tidsforskydning på lytteposternes interne ur samt isdækket i Roskilde Fjord. Tidsforskydningerne på lytteposternes interne ur varierede fra 4 sekunder til 23 minutter. Dette medførte f.eks., at fisk, som i reel tid blev registreret kl. 12:00, ville fremgå som værende blevet registreret kl. 12:23. I sammenarbejde med VEMCO (lyttepostproducenten) udarbejdede jeg en løsning, som fik rettet op på fejlen. Undervejs i projektet, vinter 2018, frøs dele af Roskilde Fjord. Erfaring fra lignende projekter har vist, at isdække kan skade og sænke lytteposterne og herved forårsage tab af udstyr. For at imødegå denne problemstilling blev der udarbejdet en handleplan for, hvorledes vi fortsat kunne samle data i måneder med isdække og undgå at miste udstyr i fjorden. Det blev vedtaget, at alle flagbøjer skulle afmonteres og erstattes med undervandsbøjer. Undervandsbøjerne, blev monteret således at undervandsbøjen samt lytteposten var ca. 1 meter under havoverfladen. Dette gjorde at isflager, ikke ødelagde vores udstyr. For at sikre fuld funktionalitet og forebygge eventuelle tab, foretog jeg i disse perioder minimum en felttur om ugen (i de isfri områder af Roskilde fjord). Efter at have testet størstedelen af alle lytteposter kunne vi bekræfte, at lytteposterne var fuldt ud funktionelle i disse perioder.

Manuel pejling

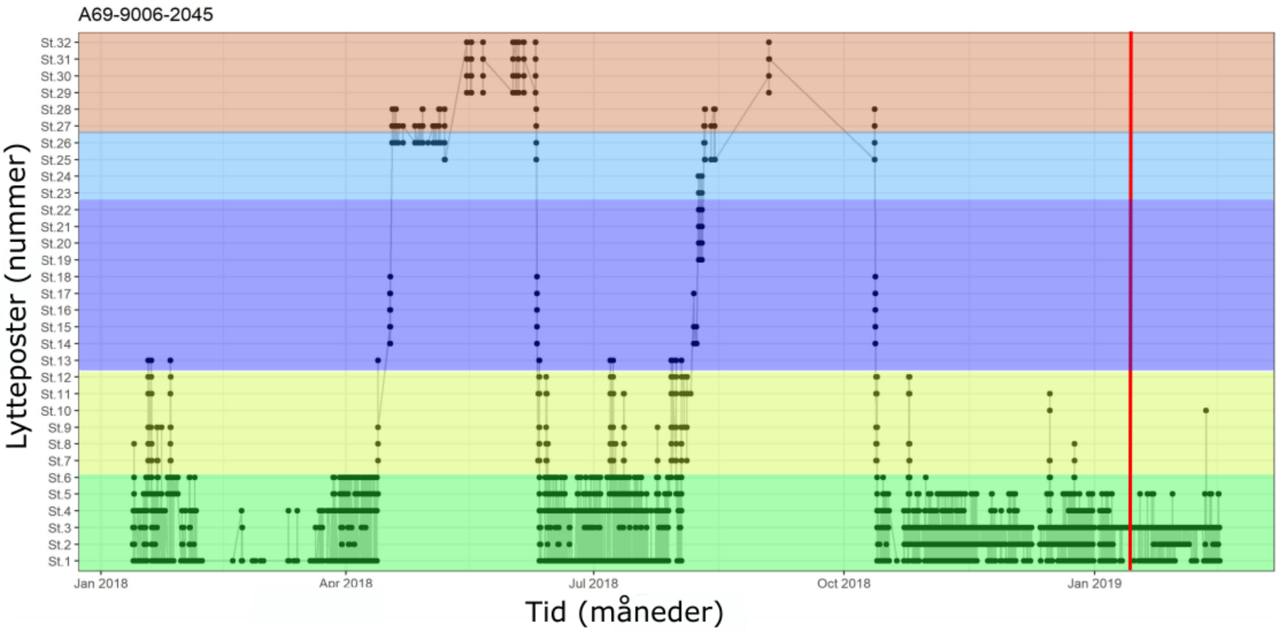
Ved at anvende en håndholdt manuel pejler (VEMCO, 2019c) var det muligt at spore havørredernes vandring i områder, hvor der ikke var lytteposter. Manuel pejling af mærkede havørreder blev fortaget inden- og uden for det marint beskyttede område. Dette var med henblik på at registrere havørreder, som var uden for de stationære lytteposters rækkevidde. Herved kunne dødelighed estimeres når fik holdt op med at bevæge sig. Ved at anvende den manuelle pejler på månedligbasis kunne vi bestemme, om der var havørreder tilstede inde i det marint beskyttede område, men uden for lytteposternes rækkevidde. Den manuelle pejling af mærkede havørreder blev primært fortaget af Jonn Poulsen og Kim Jørgensen.



Figur 5 viser den manuelle pejler, som blev anvendt i dette studie (VR100; foto B) samt lytteudstyret, der opfanger de akustiske signaler, som havørreder mærket med akustiske transmittere udsender (foto A).

Databehandling og analyse

Data fra den de stationære lytteposter og den manuelle pejling blev behandlet i R (R Core Team, 2019). Helt specifikt blev der anvendt komponenter fra R pakken (Flávio, 2019). De specifikke delkomponenter, som blev anvendt fra R pakken, var data sortering og estimering af bevægelighedsmønstre. For at verificere korrekt databehandling og undgå fejl og mangler i de udarbejdede scripts, blev der med ca. to ugers mellemrum afholdt møder med R pakkens udvikler Hugo M. Flávio. Udover behandling, analyse og beregninger fortaget i R blev dele af data gennemgået manuelt. Dette var blandt andet for at estimere dødstidspunkt for havørreder, som gik tabt inde i det marint beskyttede område. Ved at anvende R kunne vi på baggrund af de individuelle havørreders bevægelser visualisere og analysere havørredernes tilstedeværelse og tid brugt inde i det marint beskyttede område. For hver enkelt havørred blev der udarbejdet et ”bevægelses datasæt”. Dette datasæt indeholdt den samlede tid, som hver enkelt havørred brugte i det marint beskyttede område. På baggrund af dette datasæt blev der lavet en visualisering af alle mærkede havørreders bevægelsesmønster i fjorden. Et visuelt eksempel heraf kan ses i figur 6 nedenfor, hvor bevægelsesmønsteret for havørred med identifikationsnummeret A96-9006-2045 er præsenteret.



Figur 6 viser bevægelsesmønsteret for en havørred mærket med en akustisk transmitter med ID-nummeret A69-9006-2045. De sorte prikker viser registreringer af det akustiske signal på en given station. Stregerne imellem de sorte prikker viser bevægelsen, som pågældende havørred har foretaget. Y-aksen viser lyttepostnummeret. Lyttepost 1 til 6 (grøn skravering) er i Kattinge Vig (det marint beskyttede område), lyttepost 7 til 12 (gul skravering) er i udmundingen af Kattinge Vig (det marint beskyttede område), lyttepost 13 til 22 (lilla skravering) viser lytteposter ved Eskilsø, lyttepost 23 til 26 (blå skravering) viser lytteposter ved Frederikssund, og lyttepost 27 til 32 (rød skravering) viser lytteposter ved Dyrnæs. Den røde vertikale streg viser, hvornår studiet stoppede. På denne figur kan man f.eks. se, at havørreden i midten af april vandrede fra det marint beskyttede område (grønt skraverede område) til Dyrnæs (rød skraverede område).

Udover databehandlingen i R blev dele af data fra hhv. manuel pejling og de stationære lytteposter gennemgået manuelt. Herigennem var det muligt at estimere dødstidspunktet for havørreder, som døde inde i det marint beskyttede område.

GIS kort

Alle kort præsenteret i det skriftlige udkast til artiklen er produceret i ArcGIS (figur 1 og 3). Samtlige kort er udarbejdet på Geus (Københavns Universitet, Øster Voldgade 10). På nuværende tidspunkt er der ingen offentligt tilgængelige kort, som præsenterer hvorledes Langvad Å skal flyttes. Derfor blev der gennem en længere periode i foråret 2019 fortaget flere telefonsamtaler med projektansvarlige fra hhv. Niras (Allerød) og Roskilde Kommune. Niras tilsendte et håndlavet kort, hvorefter jeg udarbejdede GIS kortene, som er præsenteret i det skriftlige dokument.

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Master Thesis

Using acoustic fish telemetry to evaluate impact of river diverging: implications for anadromous brown trout (*Salmo trutta*) utilizing a marine protected area

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Abstract

Globally, policy makers are creating legislation to protect aquatic life. Within the European Union, the Water Framework Directive (WFD) targets aquatic life and highlights the importance of eliminating migration barriers and ensuring free passage for riverine organisms. This study investigates a case where free passage is ensured for brown trout (*Salmo trutta*; termed trout) by diverging a stream (Langvad Stream) to a different stream channel. While diverging the stream will circumvent a migration barrier, it also means that the stream mouth will be diverged away from an area inside a marine protected area (MPA) to an area outside of the MPA. This could hamper the marine survival of the trout; however, the marine survival and the impact of the MPA to protect the trout are largely unknown. This is particularly pertinent, because trout is a migratory species that may leave the MPA shortly after entering the marine environment. Using acoustic telemetry, this study investigated the efficacy of the MPA to protect post-spawning trout and estimated 1) the time spent inside and outside of the MPA, and 2) the loss of brown trout inside and outside of the MPA. Overall, tracking data revealed that trout were present inside the MPA during all seasons and spent on average 67.4% (± 4.5% SE) of the time inside the MPA. Brown trout surviving the entire study period spent on average 50.6% (± 8.4% SE) of the time inside the MPA. In total, 77% of the brown trout were lost during the study period and did not return to the Langvad Stream to spawn. The loss of brown trout was unevenly divided inside (n = 14) and outside (n = 22) of the MPA. The Langvad Stream is not reaching the goal of the WFD (80 juvenile trout 100m^{-2}), suggesting that further measures are required to enhance trout survival and production. Effects of the planned stream diversion on trout survival and production are uncertain, and the Langvad Stream is unlikely to meet the WFD goal after the diversion. We recommend that alternative solutions to meet the WFD are considered, including a different diverging route and expansion of the MPA both in terms of area coverage and associated fishing restrictions

Introduction

Extensive habitat degradation and overexploitation of living marine resources affect many marine coastal areas (Lotze et al. 2006; Kristensen et al. 2017). As a result, conservation and restoration of fish and fisheries are major environmental challenges (Balmford et al. 2005). To protect coastal marine species and ecosystems, implementation of marine protected areas (MPAs) is recognized as a promising management tool (Lester et al. 2009; Gaines, Lester, Grorud-Colvert, Costello, & Pollnac, 2010). MPAs are areas in the ocean where fishing and/or other extractive activities are restricted or prohibited as no-take zones (marine reserves) (IUCN & WCPA, 2018). Embraced by high level international bodies as a tool to achieve biodiversity goals, MPAs have been subject to rapid growth in recent decades. Currently, approximately 6.4 % of the world’s ocean is covered by MPAs (IUCN, 2017), largely due to international treaties such as Convention on Biological Diversity (CBD) (CBD, 2017). Under the CBD, the goal is that 10 % of the global coastal and marine areas will be covered by MPAs in 2020 (CBD, 2017). However, MPA area coverage alone will not necessarily optimize protection for marine biodiversity, nor reflect the MPA’s conservation and protective efficacy (Kerwath et al. 2009; Edgar, 2011; Edgar et al. 2014). Instead, optimal MPAs efficacy depends on various factors, including degree of fishing permitted inside of the MPA, level of enforcement, MPA age, and the presence of continuous habitat allowing fish movement across MPA boundaries and positioning of the MPA (Edgar, 2011; Edgard et al. 2014). Effects of MPAs have been widely documented showing increase in fish abundance, biomass, individual size and egg production both inside the MPA (Lester et al. 2009) and outside the MPA as a spillover effect (Goñi, Hilborn, Díaz, Mallol, & Adlerstein, 2010; Abesamis & Russ, 2005). Because individual fish survival is positively related to the time spent inside an MPA (Palumbi, 2004), exit from the MPA often causes elevated individual mortality (Edgar, 2011). MPAs are mainly expected to protect less mobile and sedentary fish species (Pilyugin, Medlock, & Leenheer, 2016), but positive MPA effects have also been documented for mobile and migratory species (Kerwath et al. 2009; Claudet et al. 2010; Knip, Heupel, & Simpfendorfer, 2012).

Migration is considered an adaptation to spatiotemporal fluctuations in resources, where synchronized movements between distinct habitats occur at different life stages (Dingle & Drake 2007; Lucas & Baras, 2001). Anadromous fish, such as the brown trout (*Salmo trutta*; henceforth termed trout), perform feeding and spawning migrations between freshwater and marine environments (Thorstad et al. 2016). Trout may adapt different strategies to optimize individual fitness, including variable periods spent at sea (Del Villar, Aarestrup, Skov, & Koed, 2014; Eldøy, 2015). Specifically, some trout may spend a few weeks at sea, whereas other trout may spend several years at sea (Klemetsen et al. 2003). Therefore, measuring and predicting the efficacy of an MPA to protect trout remains difficult.

European Union (EU) member states act in agreement with the Water Framework Directive (WFD). By employing and implementing EU management measures into national legislation, the purpose of the WFD is to prevent deterioration, protect and enhance surface water bodies (European Commission, 2003). By integrating the WFD management measures into national policy, EU member states are currently conforming with the legislative goals described in the second management cycle (2015-2021) of the WFD. This entails protection and enhancement of surface water bodies, including removal of waterway obstructions and to achieve good ecological status (GES) for surface waterbodies (Miljø- og Fødevareministeriet, 2016; European Commission, 2003). Each member state is required to define reference conditions (i.e. assumed pristine conditions) for surface water bodies. Once reference conditions have been established, the ecological status of similar national surface waterbodies is evaluated. The ecological status is classified by various biological, chemical, hydro morphological and physical elements (Bonde et al. 2006). Good ecological status (GES) is by default the objective for all WFD waterbodies. The ecological status of many rivers and streams in Denmark must comply with measures as stipulated in the DFFVø trout index. To achieve GES in compliance with the DFFVø trout index, the density of juvenile trout must be at least 80 individuals 100m^{-2} in small streams (i.e. below 2 m in stream width) (Nielsen, Sivebæk, & Baktoft, 2016). In addition to the DFFVø trout index requirements, Denmark is required to remove all obstacles restricting fish migration (Miljø- og Fødevareministeriet, 2016; European Commission, 2003).

In Denmark, trout are predominantly caught for recreational purposes using a diversity of gears, including gillnets and rod and line fishing (Hayes, Ferreri, & Taylor, 2012; Gislason et al. 2014). In the past two decades, many Danish trout populations have experienced a steady increase, primarily due to restoration of spawning and rearing habitats, removal of obstacles, small scale MPAs and stocking with indigenous juvenile trout (Sivebæk, 2018). A range of regulative measures protect trout, including a seasonal harvest ban on spawning colored trout (November 16th – January 15th) and a 500-meter closed zone surrounding many river mouths (Fiskeristyrelsen, 2019). Seasonal harvest ban and closed zones are employed to protect trout, primarily during the spawning season when trout abundance increases near river mouths and in the rivers.

In 2005, the Danish fisheries agency implemented an MPA in the Roskilde Fjord, covering the entire Kattinge Bay area and the outlet of the Langvad Stream (Figure 2). The trout population in the Langvad Stream had deteriorated because of several factors, including; 1) a weir near the outlet of the Langvad Stream despite the presence of a pool and weir fish passage (Clay, 2017; Figure 2), 2) the Langvad Stream running through three separate lakes (Figure 2) and 3) estimates of trout experiencing high marine mortality (Fiskeridirektoratet, 2003). The weir limited fish passage and the lakes caused elevated fish mortality, particularly relevant for trout smolts passing through the lakes (Jepsen, Aarestrup, Økland, & Rasmussen, 1998). The MPA implementation in 2005 meant that gill netting and lure trolling became prohibited fishing techniques throughout the year.

To comply with the WFD and ensure GES (in accordance with the DFFVø trout index) in the Langvad Stream, the stream is scheduled to be diverged (Figure 2) into the Gedebæk Stream (Figure 2). The objective of the stream diverging is to circumvent the weir near the stream outlet (Figure 2) to provide free passage and to reach GES in compliance with the DFFVø trout index. The new outlet of the Langvad Stream will be located outside of Kattinge Bay, thus outside of the MPA (Figure 2). After the stream diverging, trout leaving the Langvad stream will no longer enter directly into the MPA. Instead, the trout will enter a marine area where both lure trolling and gill net fishing are permitted fishing techniques. The impact of the stream diverging on trout marine survival is uncertain as the protection currently provided by the MPA is unknown.

Using telemetry, this study examined the ability of the Kattinge Bay MPA to protect adult trout in the Roskilde Fjord. Specifically, the individual trout residence times inside and outside of the MPA were estimated by tagging and tracking trout for a 1-year period. This was accomplished using stationary receivers combined with manual tracking of the trout in the Roskilde Fjord. Using the tracking data, the loss of individual trout was estimated inside and outside of the MPA. If trout leaving the Langvad Stream are also quickly leaving the Roskilde Fjord for foraging elsewhere (e.g. Kattegat Sea; Figure 1), the fishing restrictions inside the MPA are probably providing limited protection of the trout. This migratory pattern would be in agreement with recent trout studies in neighboring fjord systems (Kristensen, Birnie-Gauvin, & Aarestrup, 2019). On the other hand, trout could be residing in the MPA for a substantial duration (i.e. months) in which case the MPA is expected to protect the trout from gill netting and lure trolling. If the trout tend to remain in the fjord, but both inside and outside of the MPA, expanding the MPA might be a useful tool to enhance the protection of the trout from fisheries and enable a viable population of adult and juvenile trout in agreement with the WFD.

Methods

Study site

The study was conducted in Roskilde Fjord (55° 48' 36" N, 12° 03' 36” E; 117 km^2) in eastern Denmark. The Roskilde Fjord is approximately 40 km long and is draining into the southern part of the Kattegat Sea (Figure 1). The Roskilde Fjord is generally shallow with water depths rarely exceeding 6 meters. The Kattinge Bay (3.82 km^2) is located in the southern part of the fjord (Figure 1). Comparable to the rest of the fjord, Kattinge Bay is shallow, except in a limited area where the water depth is reaching 17 m (55° 40’ 37" N, 12° 01’ 08" E). The Kattinge Bay was appointed as an MPA in 2005 based on estimates of high trout abundance in autumn and spring. The Langvad Stream drains into the south-western part of Kattinge Bay. Importantly, smolt mortality surveys revealed 88% mortality for seaward migrating smolts passing the three interconnected lakes in the Langvad Stream system (Henriksen, 1998; Figure 2). These findings are in agreement with other studies investigating impacts of lakes on smolt mortality (Schwinn, Aarestrup, Baktoft, & Koed, 2017; Jepsen et al. 1998). Near the outlet, stream discharge from the Langvad Stream is controlled by a sluice, regulating water levels in the three lakes further upstream, and draining parts of the water into the pool and weir fish passage (Figure 2). To recover to trout population, juvenile trout are released in the Langvad Stream and smolts are released in the outlet of the Langvad Stream. Approximately 8000 smolts are released in the outlet of the Langvad Stream on a yearly basis, whereas approximately 3000 juvenile trout are released in the Langvad Stream every third year.

Stationary receivers

To track tagged trout, a network of 32 VR2W Vemco receivers were deployed throughout the southern and central parts of the Roskilde Fjord (Figure 1). All receivers were positioned 1 m below the water surface and deployed at water depths varying between 1.7 – 17 meters. The receivers were all attached to two coupled moorings (according to VEMCO standards (VEMCO, 2019b)) and kept afloat and in place by surface buoys. In addition, one receiver was located upstream of the weir in Store Kattinge Lake (Figure 2). Receivers were cleaned and data were downloaded on a bimonthly basis. Test transmitters were used to confirm that all receivers worked correctly throughout the 1-year study period. To determine individual residence time and loss inside and outside of the MPA, the hydrophones were deployed to cover key points in the fjord (Figure 1). Utilizing geographically narrow passages (170-830 meters), the deployment of hydrophones ensured detection of trout emigrating from the MPA. This was confirmed using test transmitters (range tests; VEMCO, 2019a) and manual tracking of the trout, both inside and outside of the MPA.

Manual tracking from a boat

Using a portable receiver (VR100; VEMCO, 2019b), manual tracking was performed on a monthly basis to locate tagged trout both inside and outside of the MPA. Manual tracking mainly targeted areas that were outside of the detection range of the stationary receivers (Figure 2). Thus, trout were often detected by the manual tracking if the fish were located outside of receiver detection range. By repeatedly returning to the same GPS locations, it was estimated if the trout were moving or had become immobile. Combining VR100 data and data from the stationary receivers (Figure 2), it was estimated if trout were lost inside the MPA without emigrating from the MPA.

Fish capture and tagging

Upstream migrating trout (n = 50, mean total body length = 54.9 ± 5.8 cm; range = 45 to 72 cm) were caught using a Wolf trap deployed in Langvad Stream between 1st November 2017 and 12th January 2018. The trap was situated in the stream, 100 m from the Kattinge Bay. Due to low numbers of trout entering the Langvad Stream, tagging and release were conducted on two separate days: 14th December 2017 and 12th January 2018. During the trapping period, 56 trout entered the Langvad

Stream. Captured fish were transferred to two flow-through (5000 liter each) holding tanks with oxygenated water and kept until tagging (on 14th December 2017 and 12th January 2018). As fish matured in the holding tank, fish were stripped for sperm and eggs and returned to the holding tanks. Prior to tagging, fish were anesthetized according to standards described previously (Geertz-Hansen, Koed, & Sivebæk, 2013). Fish were tagged using 69 kHz V13T coded Vemco transmitters (Dimensions = 13x48mm, weight in air = 13 grams, power output = 152dB, estimated battery life 502 days, time lag between signal emission (nominal delay) = 120 ± 60 s). Transmitters were equipped with a thermal sensor to record and transmit temperature data. The transmitted temperature data meant that mammalian and avian predation could be detected by spike in transmitted temperature data, if the predator ingested the transmitter and remained in the water (Wahlberg et al. 2014). All transmitters were surgically implanted into the abdominal cavity following previous studies (Aarestrup, Jepsen, Rasmussen, & Økland, 1999). Once fully recovered from anesthesia (Geertz-Hansen et al. 2013), fish were returned to Langvad Stream downstream of weir (Figure 2). After release, trout entered the MPA directly when they left the stream.

All experimental procedures were approved by the Danish Experimental Animal Committee and carried out in accordance with present regulation. All handling, anesthesia and tagging procedures were performed in agreement with a license provided to the Technical University of Denmark for animal experimentation (license 2017-15-0201-01164).

Acquisition and analysis of fish telemetry data

Analyses of tracking data included telemetry data covering a 1-year period spanning the period 12th of January 2018 - 12th of January 2019. A total of 50 trout were trapped, tagged and released in the Langvad Stream. Data analysis was divided into two fish groups: 1) analysis of all the released fish (n = 50) and 2) analysis of the fish that survived the entire 1-year study period (n = 11).

Rules for estimating trout presence inside and outside the MPA

Analyses of fish movements inside and outside of the MPA were conducted in agreement with previous MPA studies examining fish residence times (Kerwath et al. 2009). To determine if the fish stayed inside the MPA or left the MPA area, the receiver network was divided into three groups (Figure 1). Group 1 covered receivers deployed inside the western part of the MPA in Kattinge Bay (n = 6), group 2 covered receivers deployed at the exit of the MPA (n = 6) and group 3 covered receivers deployed in three areas in the Roskilde Fjord outside of the MPA (n = 19, Figure 1). In addition, one receiver was located upstream of the weir in Store Kattinge Lake (Figure 2).

Trout were estimated to be inside or outside of the MPA according to a simple set of movement rules, similar to Kerwath et al. (2009). The rules were developed using test transmitters applied in numerous locations in the Roskilde Fjord combined with known fish locations revealed by the manual tracking inside and outside of the MPA. The movement rules were: After release into the outlet of the Langvad Stream, trout were assumed to be inside the MPA until first detection by receivers in group 2 (Figure 1). Upon detection by the receivers in group 2, fish were considered as outside of the MPA until they were detected again by the receivers in group 1 (Figure 1). Trout detected on the receiver in Store Kattinge Lake (upstream of the weir) were considered outside the MPA. Thus, upstream migrating trout entering the Langvad Stream were not considered inside the MPA.

Time spent inside and outside of the MPA

The analyses of time spend inside the MPA resembled previous telemetry studies determining time spent inside MPAs (Knip et al. 2012). To calculate the amount of time each trout spent inside the MPA, the periods when fish were present inside the MPA were summed.

To calculate the proportion of time each fish spent inside the MPA, the time spent inside the MPA was divided with the total time in which the trout was detected (time spanned between first detection inside the MPA and last detection). For all trout entering the Langvad Stream, time spent in the stream was subtracted from the total time spent inside the MPA. For trout that were lost during the 1-year study period, the total time in which the trout was detected span from the first detection inside the MPA (i.e. any receiver inside the MPA) until the estimated loss occurred (inside or outside of the MPA). Importantly, this approach may overestimate the time spent inside the MPA. For example, if a trout emigrated from the Langvad Stream and remained inside the MPA but was removed from MPA after 60 days (e.g. by fishing), the proportion of time spent inside the MPA approached 100% (60 days divided by 60 days and multiplied by 100%).

Trout survival throughout the 1-year study period was assumed when the fish was still moving actively towards the study termination. For example, trout entering the MPA in October and moving actively between receivers located inside or outside the MPA 72 hours prior to study termination were estimated as survivors.

For trout surviving the full 1-year study period, the total time in which the trout was detected span from the first detection inside the MPA (i.e. any receiver inside the MPA) and until the last detection shortly before the study termination (12th of January 2019). For example, if a trout surviving the entire 1-year study period spent 5 months inside the MPA, residence time inside the MPA was estimated to 41.7% (i.e. 5 months divided by 12 months and multiplied by 100%).

Estimating trout loss inside and outside of the MPA

Similar to previous studies (Aldvén, Hedger, Økland, Rivinoja, & Höjesjö, 2015; Thorbjørnsen et al. 2018), absolute trout loss was quantified for fish residing inside and outside the MPA. Trout were considered lost when transmitters were returned by local fishermen, when fish failed to return to the Langvad Stream during the subsequent spawning season (starting in October) or if horizontal movement completely ceased for more than four months. For trout that ceased to move for at least four months, thereby considered dead, time of mortality was estimated and remaining data were removed from the dataset. Time of mortality for the individuals that ceased to perform horizontal movements (n =3) was estimated based on last evidence of active movement. To confirm trout movements as revealed by the stationary receivers, data from manual tracking were included and analyzed. The manual tracking revealed if trout were outside of stationary receiver detection range, and if so, manual tracking data revealed if trout outside of stationary receiver range were moving or immobile.

Statistical analyses and applied software

Fishers exact test was applied to compare mortality, respectively inside and outside the MPA. Results were considered significant if $\alpha < 0.05$. Data were downloaded from all receivers using the VUE software (Version 2.6.1, Vemco Ltd., Halifax, Canada). All values are reported as means ± standard error of the mean, unless noted otherwise. All calculations and analyses were performed in R (R Core Team, 2019).

Results

In total, 50 trout were captured, tagged and released in the Langvad Stream (Figure 2). Three trout were excluded from the study, as they were not detected during the 1-year study period. The remaining 47 trout generated 2,523,761 detections, after accounting for transmitter collisions and false detections.

Trout utilization of the MPA was substantial but also versatile. Trout were present inside the MPA throughout the 1-year study period. On average, all trout spent 67.4% (± 4.5%) of the time inside the MPA. For trout that did not survive the full study period, this estimate included the period of time spent inside the MPA and until the estimated loss occurred. As indicated above, this approach may inflate the percentage of time spent inside the MPA. Data for trout that survived throughout the full study period (n = 11) were used to produce more accurate estimates of the percentage of time spent inside the MPA. The surviving trout spent on average 50.6% (± 8.4%) of the time (i.e. approximately 6 months) inside the MPA. Utilization of the MPA among the surviving trout tended to vary with season. Specifically, the highest percentage of the trout were present inside the MPA during winter, spring and the late autumn, with fewer trout present inside the MPA during summer and early autumn (Figure 3).

Trout adopted different behavioral strategies. Throughout the 1-year study period, 62% (n = 29) of the trout remained south of Frederikssund whereas 38% (n = 18) migrated north of Frederikssund (Figure 1). These estimates included both surviving and lost trout. For the surviving trout (n = 11) alone, the distributions were as follows A) five trout migrated north of Frederikssund and spent on average 38.2% of time inside the MPA, B) four trout remained south of Frederikssund and spent on average 38.1% of time inside the MPA and two trout resided inside the MPA throughout the entire 1-year study period, performing only minor excursions from the MPA. These trout spent on average 97.5% time inside the MPA. None of the tagged trout re-entered the Langvad Stream during the 1-year study period.

The total trout survival throughout the entire study period was 23% (11 surviving and 36 lost trout). Trout loss was higher outside of the MPA (47%, n = 22) than inside of the MPA (30%, n = 14). Fishers exact revealed no significant difference between fish mortality inside and outside the MPA (Fisher’s exact test; $p = 0.297$).

Among the 14 trout that were lost inside the MPA, data scrutiny revealed that three of them ceased to perform horizontal movements. The remaining 11 trout that were lost inside the MPA disappeared from the area inside the MPA. Manual tracking data confirmed that none of these 11 transmitters associated with trout lost inside the MPA were present inside the MPA after the last detection by the stationary receivers. These findings indicated that three trout died inside the MPA whereas 11 were removed from the MPA, presumably as a consequence of fishing activities.

Three transmitters from recaptured trout were retrieved from local fishermen, providing evidence of fishing induced mortality. All three recaptured trout where caught using gillnets outside of the MPA.

By the end of the 1-year study period, 9 of 11 surviving trout were present inside the MPA, the remaining two trout were still moving outside of the MPA (Figure 2). Data analysis revealed that the two trout residing outside of the MPA at the end of the study period, reentered the MPA between October and November 2018, but left the MPA before the study termination. Illegal gillnetting was observed inside the MPA on at least three occasions, but catches were not quantified. Similarly, illegal angling was observed in the river mouth of the Langvad Stream (i.e. within the 500 m closed zone surrounding the stream mouth).

Discussion

The use of MPAs as a mean to protect aquatic life is growing globally (Gaines et al. 2010), however, but it remains controversial whether MPAs are protecting mobile species (Kerwath et al. 2009). Being the first study to investigate MPA efficacy using fish telemetry in Denmark, the present study evaluated whether trout may benefit from protection afforded by a small MPA and estimated the marine mortality inside and outside of the MPA. The present study found that trout spent on average 67% time inside the MPA. It is important to note that this average number could be inflated by the fact that trout that were lost inside the MPA could have a 100% residence time inside the MPA, even if they only spent a relatively short period of time inside the MPA (e.g. weeks). This contrasts with the data representing the surviving trout spending on average 50% time inside the MPA, where the residence time inside the MPA could be estimated more accurately and was performed in agreement with methods described by Knip et al. (2012).

Previous studies have revealed that the protection afforded by MPAs for mobile species depends on the time spent inside the MPA by the individual fish (Palumbi, 2004; Kerwath et al. 2009; Knip et al. 2012). The present study found that all trout on average spent 67% time inside the MPA and that surviving trout spent on average 50.4 time inside the MPA. These percentages exceed percentages reported by a previous trout study that quantified time spent inside an MPA. Specifically, Thorbjørnsen et al. (2018) reported that trout spent 32% of the time, during a 1-year period, inside an MPA in Norway.

It remains controversial whether MPAs may protect mobile species. It has been suggested that many target species are too mobile to benefit from the protection afforded by area-based management, such as MPAs, and that only resident species benefit from protection afforded by MPAs (FSBI, 2001; Polunin, 2004; Botsford, Micheli, & Hastings, 2003; Sale et al. 2005; Pilyugin et al. 2016). The general preconception is that highly migratory species disperse outside the boundary of MPAs, indicating that large MPAs are required to protect mobile species (FSBI, 2001; Polunin, 2004; Palumbi, 2004; Micheli, Halpern, Botsford, & Warner, 2004; Sale et al. 2005). Using mathematical models, the preconception that mobile species may only benefit from large MPAs has demonstrated by several studies (Guenette & Walters, 2000; Holland, 2000; Botsford et al. 2003; Stefansson & Rosenberg, 2006). On the other hand, mounting evidence based on acoustic fish telemetry reveals that MPAs may provide at least partial protection to mobile species. For example, average percentages spent inside small MPAs range between 32% per year for trout (Thorbjørnsen et al. 2018) to >50% per year for white stumpnose (*Rhabdosargus globiceps*) (Kerwath et al. 2009). The present study revealed that the average trout spent >50% of the time inside a small MPA, indicating that the small MPA provided substantial protection to the fish. Although fishing may be inflated outside of a MPA, potentially eliminating any protective benefits afforded by the MPA (Palumbi, 2004), these findings add to the mounting evidence supporting that small MPAs may provide protection, even to mobile species (Morris & Green, 2012; Kerwath et al. 2009; Thorbjørnsen et al. 2018).

The present study found that 77% of all trout were lost in the 1-year study period. In total, 30% (n = 14) and 47% (n = 22) of all trout were lost inside and outside of the MPA, respectively. Potentially, the estimated loss could be affected by uncommon fish behaviors. In anadromous species, straying (Keefer & Caudill, 2014; Thorstad et al. 2016) or non-consecutive repeat spawning behavior (Rideout, Rose, & Burton, 2005; Jonsson & Jonsson, 2009) may occur and could affect the present results, but we assume that the marine loss (77%) largely corresponds to marine mortality (including fishing induced mortality). Previous salmonid studies have provided mortality estimates that vary substantially between years and locations (Jonsson and Jonsson, 2009; Aldvén et al. 2015). Annual marine mortality may differ between 15% (Thorstad et al. 2016) and 85% (Berg & Jonsson, 1990; Aarestrup et al. 2015; Kristensen et al. 2019). The marine mortality estimated by the present study (77%) reflects an investigation lasting one year and in one location (Roskilde Fjord), indicating that the estimated annual mortality should be interpreted with caution.

Marine mortality of salmonids may be influenced by several factors (Sobocinski, Greene, & Schmidt, 2018), including environmental conditions (Gosselin et al. 2018), predation by birds (Wiese, Parrish, Thompson, & Maranto, 2008), predation by seals (Eero et al. 2011), predation by pike (*Esox Lucius*) (Frost, 1954) and fishing (Kerwath et al. 2009; Morris & Green, 2012; Thorstad et al. 2016). Whether pike occur in Roskilde Fjord remains uncertain, but harbour seals *(Phoca Vitulina)* are known to reside in Roskilde Fjord and may target salmonid species (Thomas, Nelson, Lance, Deagle, & Trites, 2017; Wright, Riemer, Brown, Ougzin, & Bucklin, 2007). Previous studies have documented that temperatures recorded by fish telemetry equipment may increase if the tagged fish are consumed by mammalian predators (Wahlberg et al. 2014). This was not observed in the present study. In fact, transmitted temperatures never approached 37 degrees C as would be expected if the transmitter was inside a mammalian or avian predator remaining in the water. These observations indicate that predation by harbour seals is an unlikely mechanism explaining the loss of tagged fish in the present study. Previous studies have documented that cormorants (*Phalacrocorax carbo*) may consume trout and other salmonid species (Thorstad et al. 2012; Jepsen, Flávio, & Koed, 2018; Čech, Čech, Kubečka, Prchalová, & Draštík, 2019). However, the predation risk inflicted by cormorants is low for fish that are exceeding 370 mm in body length (Skov et al. 2014). In terms of salmonids, Jensen et al. 2017 found cormorant-induced mortality to be size dependent with fish larger than 380 mm experiencing no predation from cormorants. Based on such results, Čech et al. (2019) indicated that large body size may provide predation refuge. The smallest fish tagged in the present study was 45 cm and the average body length of trout that disappeared inside the MPA was 56 cm, suggesting that predation by cormorants is an unlikely mechanism explaining the losses of the tagged fish.

This study revealed trout disappearing from inside the MPA. During the 1-year study period, illegal and legal fishing was observed inside the MPA. Previous studies have documented that fishing may affect marine mortality of trout (Rasmussen & Geertz-Hansen, 2001; Kerwath et al. 2009; Sparrevohn, Storr-Paulsen, & Nielsen, 2011; Morris & Green, 2012; Thorstad et al. 2016). Sparrevohn et al. (2011) showed that recreational fishery on trout in Denmark constitute 99% (600 tones) of the total annual harvest (609 tones). The study further revealed that approximately 90% (538 tones) were caught using rod and line and that 10% were caught using gillnets (Sparrevohn et al. 2011). The minimum size for legal harvest of trout in Denmark is 40 cm (Fiskeristyrelsen, 2018). The length of trout tagged in the present study ranged between 45 and 72 cm. Because trout is the most important species to the recreational fishery and is often harvested when caught (Rasmussen & Geertz-Hansen, 2001), the present study indicates that the trout that disappeared from inside the MPA may have been harvested by legal or illegal recreational fisheries. Quantifying the relative effect of the recreational fisheries for trout inside the MPA is troublesome, primarily due to lack of data on the extent of both fisheries, as also highlighted by Kerwath et al. (2009). Future projects should aim to acquire data on fishing activity inside the MPA to investigate recreational fishing as a driver of mortality.

Since the 1990s, numerous conservation and restoration projects have aimed to recover a sustainable trout population in the Langvad Stream (e.g. restoration of spawning and rearing habitats and stocking of juvenile trout). Despite these efforts, the abundance of mature trout and density of juveniles remain low in the Langvad Stream (Henriksen, 2017). For example, Henriksen (2017) revealed poor numbers of mature trout (n = 50 to 100 per year) and low density of juvenile trout (18 juveniles per 100 m^2). To support the trout population in the Langvad Stream, managers aimed to reduce trout marine mortality by implementing the MPA in Kattinge Bay in 2005 (Fiskeridirektoratet, 2003). Implementation of the MPA entailed prohibition lure trolling and gillnet fishing inside the MPA (Fiskeridirektoratet, 2003). Although not the most important factor, Sparrevohn et al. 2011 revealed that gillnet fishing constitutes 10% of the annual harvest of trout. Based on such findings, combined with the results that trout spend on average >50% time inside the MPA, the present study may indicate that the marine mortality observed in this study could have been higher if the MPA had not been established. However, evaluating the direct effects of the MPA on trout annual marine survival is troublesome, largely due to a lack of reference conditions prior to the implementation of the MPA. These considerations are consistent with previous studies calling for data on reference conditions and specific management goals to evaluate MPAs (Nickols et al. 2019). This is particularly relevant in terms of mobile species where time spent inside the MPA is often unknown, and mortality outside of the MPA may vary depending on migration routes, foraging areas, locations of main predators etc. Importantly, the trout population in the Langvad Stream is not sustainable, and although the MPA offers some protection of the fish, the impact of the MPA is inadequate to recover a sustainable trout population in the stream.

Getting the Langvad Stream to meet the goals of the Water Framework Directive

Free fish passage and partial compliance with the WFD are ensured by circumventing the weir located in the outlet of the Langvad Stream (Figure 1). Previous studies have documented that weirs and barriers often limit migration of various fish species, including salmonids (Olesen & Aarestrup, 2006), even when fish passages are installed (Noonan et al. 2012).

The current (2017) density of juvenile trout in the Langvad Stream (18 juveniles per 100 m^2) is not meeting the GES WFD goal of 80 juveniles per 100 m^2 (Nielsen, 2016). Several factors may affect the density and production of juvenile trout, including the abundance of spawning individuals in the stream (Henriksen, 2017; Boel & Koed, 2013), predation (Riley & Marsden, 2009) and mature trout marine mortality (Harris & Milner, 2006). Previous studies have documented low numbers of upstream migrating trout in the Langvad Stream, spanning from 50 to 100 individuals every year (Henriksen, 2017). Abundances of spawning trout are influenced by several factors, including barriers (i.e. weirs; Olesen & Aarestrup, 2006), abundance of smolts emigrating from the river (Crozier & Kennedy, 1993; Elliott, 1993) and the marine mortality (Harris & Milner, 2006). Thus, several factors may explain the low numbers of mature trout and low density of juvenile trout in the Langvad stream.

Previous studies have demonstrated elevated smolt mortality when fish are passing through lakes or reservoirs. Specifically, the mortality of smolt passing one lake or reservoir may range between 74% (Schwinn, 2018) and >90% (Jepsen et al. 1998). Several studies have surveyed smolt mortality before and after the establishment of a lake (1.12 km^2) (Boel & Koed, 2013; Schwinn, 2017; Schwinn et al. 2018). Prior to the establishment of the lake, low smolt mortality ranging between 0% and 8% was observed while 74% to >90% mortality was observed after the establishment of the lake (Boel & Koed, 2013; Schwinn et al. 2017; Schwinn, 2018). These findings highlight the dramatic influence of lakes situated within stream systems. Further studies by Schwinn et al. (2017) and Schwinn et al. (2018) documented that elevated smolt mortality caused by lakes within stream systems may eradicate self-sustaining trout populations. Currently, the Langvad Stream encompass three lakes (Figure 2). All trout spawning areas are located upstream of Lake Kattinge (Henriksen, 2017). Thus, seaward migrating smolts pass through three lakes before reaching the marine environment. Consistent with other studies (Jepsen et al. 1998; Schwinn et al. 2017, Boel & Koed, 2013), Henriksen (1998) documented 88% mortality for smolts passing through the lakes situated in the Langvad Stream. Collectively, these findings suggest that a self-sustainable trout population in the Langvad Stream is dependent on a reduction in the mortality experienced by the smolts migrating between the spawning areas and the stream mouth where there is access to the marine environment.

For many salmonid species, the number of mature trout returning to a stream is proportional to the number smolt emigrants from the stream (Crozier & Kennedy, 1993; Elliott, 1993). For example, if the abundance of smolt emigrants is reduced by 50%, then the return of mature trout is also reduced by 50%. Based on these findings, it is likely that the 88% mortality of seaward migrating smolts in the Langvad Stream (Henriksen, 1998) constitute an 88% reduction in the number of returning mature trout. Thus, elevated smolt mortality through the lakes (Figure 2) plays a crucial role in terms of explaining the poor number of adult trout spawning in the Langvad Stream. To ensure a sustainable trout population in Langvad Stream, and meet the goal of the DFFVø trout index, I suggest that circumventing the lakes is a paramount element.

Finding the best route past the lakes in the Langvad Stream to enhance trout survival

Free fish passage and partial compliance with the WFD are ensured by circumventing the weir located near the outlet of the Langvad Stream**.** The present study indicates, however, that the existing plans to diverge the Langvad Stream past the weir may not result in WFD compliance in terms of juvenile trout densities in the Langvad Stream as stipulated by the DFFVø trout index. To achieve GES and compliance with the WFD with regard to juvenile trout density, I suggest that circumventing the three lakes is inevitable.

This study presents an alternative solution to the existing diverging plans. The novel solution will ensure free fish passage and circumvent the three interconnected lakes situated in the Langvad Stream (Figure 2). As indicated, interconnected lakes cause severe smolt mortality (Jepsen et al. 1998; Boel & Koed, 2013; Schwinn et al. 2017) and may eradicate trout populations (Schwinn et al. 2018). Based on such findings, I suggest an alternative solution where smolts can pass from the spawning areas to the Roskilde Fjord without passing through any lakes (Figure 2). Specifically, the Langvad Stream should drain into the Lejre Stream and eventually into the Gevninge Stream. This solution is likely to reduce the smolt mortality from 88% to 5%-26% (Jepsen et al. 1998; Boel & Koed, 2013; Schwinn et al. 2017; Schwinn, 2018). Currently, the distance between the Langvad Stream and the Lejre Stream is about 10 m, suggesting that it is feasible to allocate water from the Langvad Stream to the Lejre Stream. Water levels in the existing lakes may be maintained by allocating a limited amount of water from the Langvad Stream to the lakes, while allocating the majority of the water to the Lejre Stream (Figure 2). This alternate solution entails a relocation of the Langvad Stream outlet from inside the MPA to Lejre Bay (Figure 2). The Lejre Bay is not protected by the MPA inside Kattinge Bay and therefore, trout will not benefit from the protection from the MPA. However, the number of smolts emigrating from the Langvad Stream is anticipated to increase, thus the proportion of mature trouts returning to the Langvad Stream is also expected to increase (Crozier & Kennedy, 1993; Elliott, 1993). Although further research is required, these changes might alleviate the need for an MPA to protect the trout in the marine environment.

Relocating and improving the MPA

By implementing the MPA in Kattinge Bay in 2005, managers aimed to enhance trout marine survival (Fiskeridirektoratet, 2003). The current diverging plans entail that the outlet of the Langvad Stream will be located outside of the MPA. Therefore, trout emigrating from the Langvad Stream will not receive protection from the MPA (figure); thus, the protective benefits afforded by the existing MPA are likely to diminish. As the present diverging plans for the Langvad Stream will encompass all three lakes, smolt mortality is expected to remain at approximately 80-95% (Henriksen, 1998).

The present study revealed that 62% of all trout resided in the southern part of the Roskilde Fjord throughout the entire 1-year study period (i.e. spent 100% of the time south of Frederikssund). Specifically, 62% of the tracked fish resided south of Frederikssund, whereas the remaining 38% went north of Frederikssund. For the surviving trout, 55% (n = 6) remained south of Frederikssund, whilst 45% (n = 5) were detected at the most northern receivers located at Dyrnæs (Figure 1). These findings suggest that a large component of the trout population reside in the southern part of the Roskilde Fjord. These considerations suggest that expanding the MPA may protect a larger proportion of the trout population for an extended period. However, present results indicated that the current MPA regulations allow fishing techniques that are accounting for a large part of the mortality observed inside the MPA. The extent of legal or illegal fishing leading to trout mortality inside the MPA remains unknow, thus enhancing both regulation and enforcement may further reduce marine mortality. Specifically, converting the current MPA into a no-take marine reserve (i.e. no harvest) may ensure enhanced marine survival. Importantly, previous studies have revealed that marine reserves provide benefits superior to partially protected MPA (Lester & Halpern, 2008). Combining the alternative solution of diverging Langvad Stream to Lejre Stream (Figure 1) with a future MPA in Roskilde Fjord to protect trout, I suggest that a no-take marine reserve is established in the Lejre Bay if Langvad Stream is diverged into the Lejre Stream (Figure 1). This solution would reduce smolt mortality in the stream as well as the mortality of the trout in the marine environment. A no-take marine reserve in Lejre Bay would protect trout emigrating from the Lejre Stream. If the no-take marine reserve is extended beyond the Lejre Bay, it is likely to provide additional protection of the fish.

Using fish telemetry to investigate effects of marine protected areas.

In the present study, the receiver network was divided into three groups (figure 2). Group 2 located outside of the MPA was positioned 15-40 meters from the MPA boarder. Trout detected at group 2 were considered outside of the MPA. Combined with the detection range (up to 400-500 meter, depending on the weather etc.), the present study may have considered trout situated inside the MPA as located outside of the MPA. Thus, employing this conservative approach, trout presence inside the MPA may have been underestimated.

Small sample sizes influence whether extrapolations to the entire population can be made. The Wolf trap deployed in the Langvad Stream (Figure 2) captured all trout performing upstream migration between 1st November 2017 and 14th December 2018. Across this period, 56 mature trout were caught and 50 relatively large individuals were tagged. Therefore, despite a small sample size, it is likely that a large part of the trout population was tagged.

Conclusion

Using acoustic telemetry, this study estimated the effects of a small MPA in terms of protecting anadromous trout. Trout residence time inside the MPA was relatively high (> 50%), indicating that small MPAs may protect mobile anadromous species. The present study indicated that a substantial proportion (23% of all trout) may have been harvested by legal or illegal recreational fishing inside the MPA. Thus, implementing further fishing restrictions, such as 100% catch and release or prohibition of all fishing inside the MPA, may reduce the marine mortality.

Circumventing the weir in the Langvad Stream will comply with the goal of ensuring free fish passage as stipulated by the EU WFD. The present examination revealed that a key element to ensure a sustainable trout population and achieve GES in compliance with the DFFVø trout index is to circumvent the three interconnected lakes situated in the Langvad Stream. The current diverging plans of the Langvad Stream will not circumvent the three lakes, therefore smolt mortality in the diverged Langvad Stream likely remains unchanged. Combined with the fact that trout emigrating from the diverged Langvad Stream will not receive direct protective benefits afforded by the existing MPA, this study concluded that the planned attempt to comply with the WFD may provide a limited improvement of the juvenile trout density in the Langvad Stream.

Instead, I suggest that the Langvad Stream is diverged into the Lejre Stream combined with the establishment of a no-take marine reserve in the Lejre Bay, potentially expanded to cover the southern part of Roskilde fjord (i.e. south of Frederikssund). By diverging the river to Lejre Stream, the Langvad Stream may comply with both goals stipulated under the WFD (i.e. ensuring free fish passage and 80 juvenile trout per 100 m^2).

Figures

Figure 1

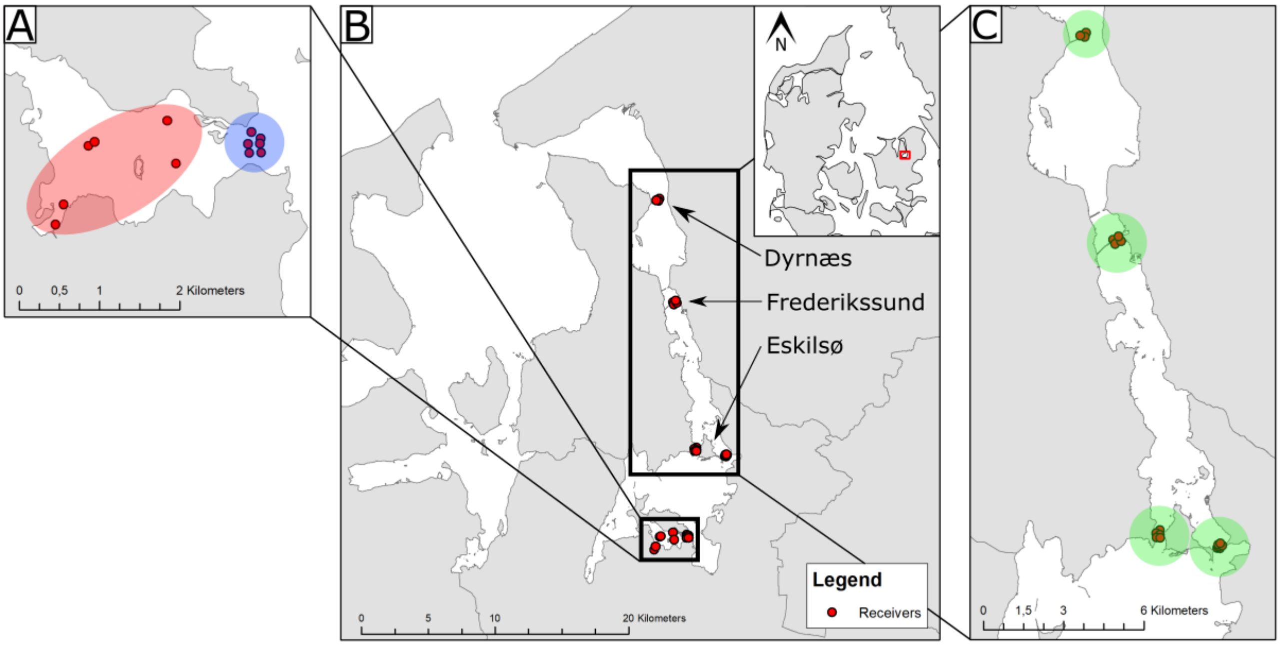

Figure 1 Map of the study site and receiver locations throughout the Roskilde Fjord, including location names for receivers deployed at Dyrnæs, Frederikssund and Eskilsø. Map A shows receiver group 1 (red) located inside the MPA and receiver group 2 (blue) located outside of the MPA. Map B shows the Roskilde Fjord including location names for receiver group 3. Map C show receiver group 3 (green) located outside of the MPA.

Figure 2

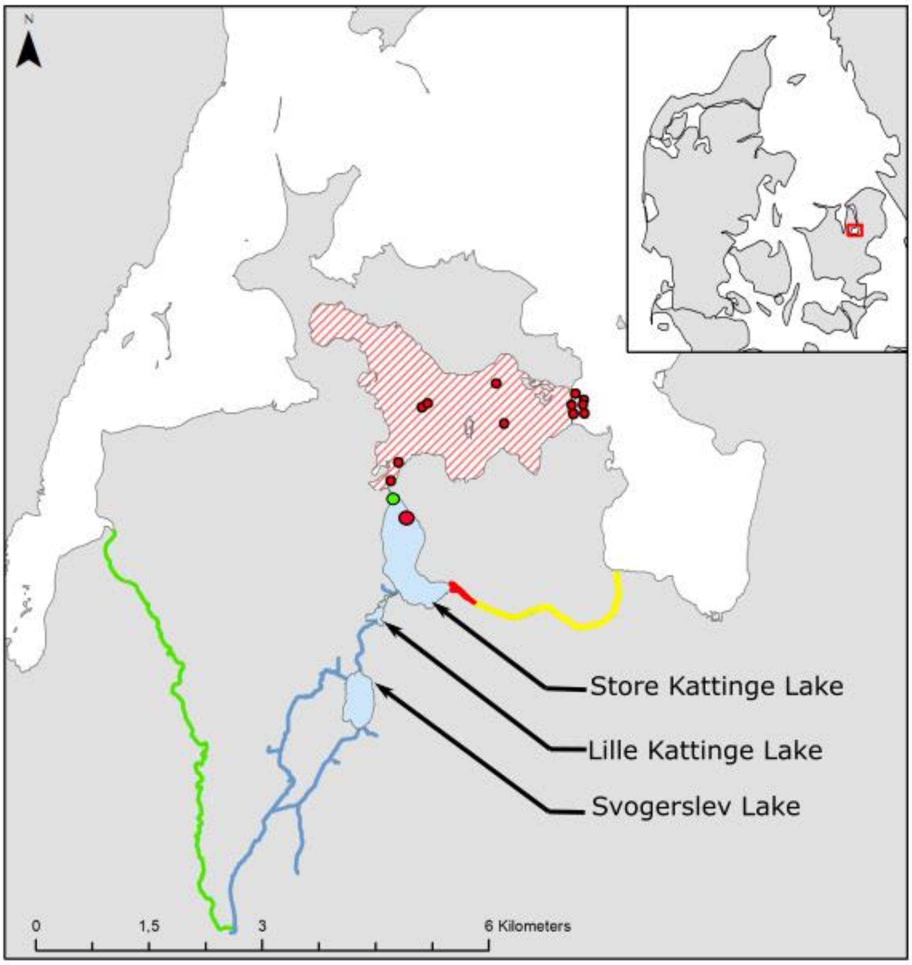

Figure 2 Map of the study site showing the MPA (red stippled line), receivers deployed inside and outside the MPA (red dots), the weir located near the outlet of the Langvad Stream (green dot), the Langvad Stream (dark blue lines), the three interconnected lakes (light blue areas), the existing diverging plan for the Langvad Stream (red line), the Gedebæk Stream (yellow line), and the alternate solution of diverging Langvad Stream to Lejre Stream and Gevning Stream (green line). Smolt performing seaward migration experience 88% mortality when passing through the three lakes (Henriksen, 1998). Spawning areas and trout rearing areas in the Langvad Stream are located upstream of the Svogerslev Lake.

Figure 3

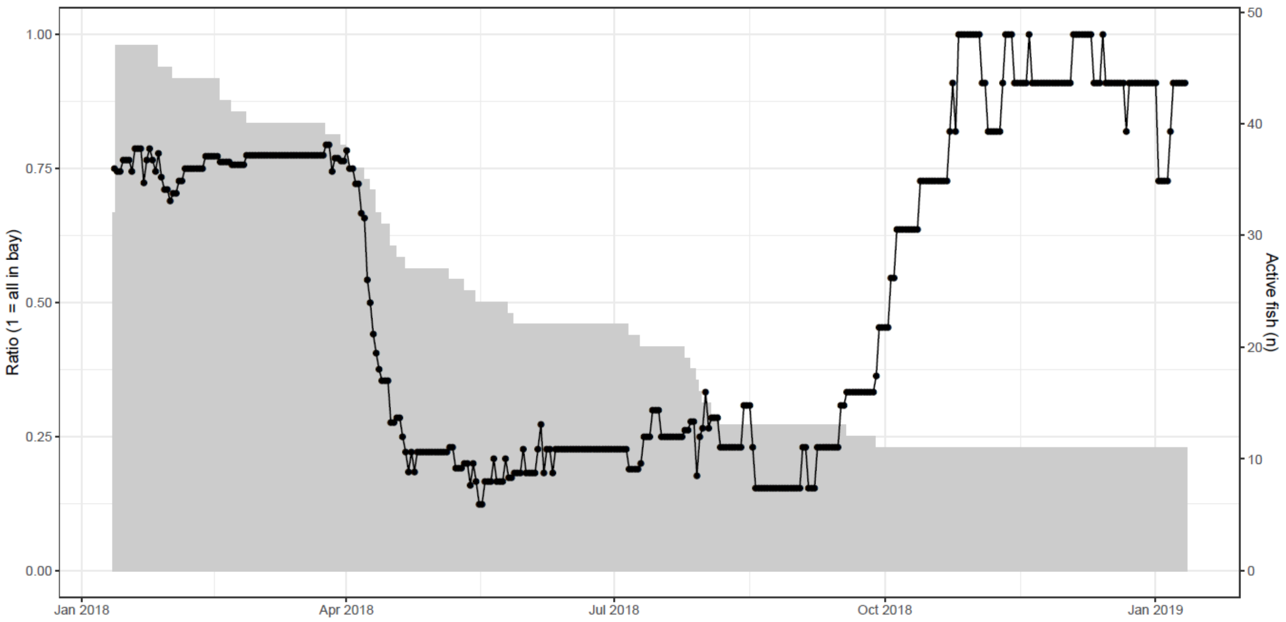

Figure 3 Trout residency inside the marine protected area (MPA) in the Kattinge Bay (Figure 2). The left y axis and the black line represents the ratio of tagged trout present inside the MPA. A ratio of 1 means that all active fish (i.e. live fish) are inside the MPA, a ratio of 0 means that all active fish (i.e. live fish) are outside the MPA. The ratio was calculated as the sum of all live fish present inside the MPA divided by the sum of all live fish situated both inside and outside of the MPA. The right y axis and the gray scaled area represent the number of live trout throughout the 1-year study period.

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